

We claim:

1. A method for measuring dry density and gravimetric water content of soil, comprising the steps of:
 - providing a plurality of spikes adapted to be driven into the soil;
 - driving said plurality of spikes into the soil in spaced relationship;
 - applying to said plurality of spikes an electrical signal suitable for time domain reflectometry;
 - analyzing a reflected signal using time domain reflectometry to determine an apparent dielectric constant K_a of the soil and bulk electrical conductivity EC_b of the soil;
 - calculating dry density ρ_d of the soil using a predetermined relationship between K_a , EC_b and ρ_d ; and
 - calculating gravimetric water content w of the soil using a predetermined relationship between K_a , EC_b , and w .
2. The method of claim 1, wherein the soil has a surface and the plurality of spikes have a lower end, and the step of analyzing a reflected signal includes measuring the apparent distance between a signal reflected from the surface of the soil and a signal reflected from the lower end of said plurality of spikes to determine an apparent length La .
3. The method of claim 2, wherein said plurality of spikes have a probe length Lp and the apparent dielectric constant $K_a = (La/Lp)^2$.
4. The method of claim 1, wherein the step of analyzing a reflected signal includes measuring a source voltage V_s of the applied signal and a long term voltage V_f of the reflected signal.
5. The method of claim 4, wherein the bulk electrical conductivity $EC_b = (1/C)(V_s/V_f - 1)$ where C is a constant related to probe length Lp .

6. The method of claim 1, wherein the predetermined relationship between K_a , EC_b and ρ_d is $\rho_d = \frac{d\sqrt{K_a} - b\sqrt{EC_b}}{ad - cb}$, where a , b , c and d are soil specific calibration constants.
7. The method of claim 6, wherein calibration constants a and b are predetermined experimentally for a given soil using the relationship $\sqrt{K_a} \frac{\rho_w}{\rho_d} = a + bw$, where ρ_w is the density of water, ρ_d is the dry density of the soil, and w is the gravimetric water content of the soil.
8. The method of claim 7, wherein EC_b is replaced with an adjusted value $EC_{b, adj}$ for which calibration constants c and d are known.
9. The method of claim 1, wherein the predetermined relationship between K_a , EC_b and w is $w = \frac{c\sqrt{K_a} - a\sqrt{EC_b}}{b\sqrt{EC_b} - d\sqrt{K_a}}$, where a , b , c and d are soil specific calibration constants.
10. The method of claim 9, wherein calibration constants c and d are predetermined experimentally for a given soil using the relationship $\sqrt{EC_b} \frac{\rho_w}{\rho_d} = c + dw$, where ρ_w is the density of water, ρ_d is the dry density of the soil, and w is the gravimetric water content of the soil.
11. The method of claim 10, wherein EC_b is replaced with an adjusted value $EC_{b, adj}$ for which calibration constants c and d are known.

12. The method of claim 11, wherein the calculated value of K_a at a given temperature is adjusted to a value $K_{a, 20^\circ C}$ at a standard temperature of $20^\circ C$, where

$$K_{a, 20^\circ C} = K_{a, T} \times TCF$$

and where TCF = Temperature Compensation Function

$$= 0.97 + 0.0015 T_{test, ^\circ C} \text{ for cohesionless soils, } 4^\circ C \leq T_{test, ^\circ C} \leq 40^\circ C$$

$$= 1.10 - 0.005 T_{test, ^\circ C} \text{ for cohesive soils, } 4^\circ C \leq T_{test, ^\circ C} \leq 40^\circ C.$$

13. A method for measuring dry density of soil, comprising the steps of:

providing a plurality of spikes adapted to be driven into the soil;

driving said plurality of spikes into the soil in spaced relationship;

applying to said plurality of spikes an electrical signal suitable for time domain

reflectometry;

analyzing a reflected signal using time domain reflectometry to determine an

apparent dielectric constant K_a of the soil and bulk electrical conductivity EC_b of the soil;

and

calculating dry density ρ_d of the soil using a predetermined relationship between

K_a , EC_b and ρ_d .

14. The method of claim 13, wherein the predetermined relationship between K_a , EC_b

and ρ_d is $\rho_d = \frac{d\sqrt{K_a} - b\sqrt{EC_b}}{ad - cb}$, where a , b , c and d are soil specific calibration

constants.

15. The method of claim 14, wherein calibration constants a and b are predetermined

experimentally for a given soil using the relationship $\sqrt{K_a} \frac{\rho_w}{\rho_d} = a + bw$, where ρ_w is the

density of water, ρ_d is the dry density of the soil, and w is the gravimetric water content of the soil.

16. The method of claim 14, wherein calibration constants c and d are predetermined experimentally for a given soil using the relationship $\sqrt{EC_b} \frac{\rho_w}{\rho_d} = c + dw$, where ρ_w is the density of water, ρ_d is the dry density of the soil, and w is the gravimetric water content of the soil.

17. The method of claim 14, wherein EC_b is replaced with an adjusted value $EC_{b, adj}$ for which calibration constants c and d are known.

18. The method of claim 17, wherein the calculated value of K_a at a given temperature is adjusted to a value $K_{a, 20^\circ C}$ at a standard temperature of $20^\circ C$, where

$$K_{a, 20^\circ C} = K_{a, T} \times TCF$$

and where TCF = Temperature Compensation Function

$$= 0.97 + 0.0015 T_{test, ^\circ C} \text{ for cohesionless soils, } 4^\circ C \leq T_{test, ^\circ C} \leq 40^\circ C$$

$$= 1.10 - 0.005 T_{test, ^\circ C} \text{ for cohesive soils, } 4^\circ C \leq T_{test, ^\circ C} \leq 40^\circ C.$$

19. A method for measuring gravimetric water content of soil, comprising the steps of:

providing a plurality of spikes adapted to be driven into the soil;

driving said plurality of spikes into the soil in spaced relationship;

applying to said plurality of spikes an electrical signal suitable for time domain reflectometry;

analyzing a reflected signal using time domain reflectometry to determine an apparent dielectric constant K_a of the soil and bulk electrical conductivity EC_b of the soil; and

calculating gravimetric water content w of the soil using a predetermined relationship between K_a , EC_b , and w .

20. The method of claim 19, wherein the predetermined relationship between K_a , EC_b and w is $w = \frac{c\sqrt{K_a} - a\sqrt{EC_b}}{b\sqrt{EC_b} - d\sqrt{K_a}}$, where a , b , c and d are soil specific calibration constants.

21. The method of claim 20, wherein calibration constants a and b are predetermined experimentally for a given soil using the relationship $\sqrt{K_a} \frac{\rho_w}{\rho_d} = a + bw$, where ρ_w is the density of water, ρ_d is the dry density of the soil, and w is the gravimetric water content of the soil.

22. The method of claim 20, wherein calibration constants c and d are predetermined experimentally for a given soil using the relationship $\sqrt{EC_b} \frac{\rho_w}{\rho_d} = c + dw$, where ρ_w is the density of water, ρ_d is the dry density of the soil, and w is the gravimetric water content of the soil.

23. The method of claim 22, wherein EC_b is replaced with an adjusted value $EC_{b, adj}$ for which calibration constants c and d are known.

24. The method of claim 23, wherein the calculated value of K_a at a given temperature is adjusted to a value $K_{a, 20^\circ C}$ at a standard temperature of $20^\circ C$, where

$$K_{a, 20^\circ C} = K_{a, T} \times TCF$$

and where TCF = Temperature Compensation Function

$$= 0.97 + 0.0015 T_{test, ^\circ C} \text{ for cohesionless soils, } 4^\circ C \leq T_{test, ^\circ C} \leq 40^\circ C$$

$$= 1.10 - 0.005 T_{test, ^\circ C} \text{ for cohesive soils, } 4^\circ C \leq T_{test, ^\circ C} \leq 40^\circ C.$$

25. An apparatus for measuring dry density of soil, comprising:
a plurality of spikes adapted to be driven into the soil in spaced relationship;
means for applying to said plurality of spikes an electrical signal suitable for time domain reflectometry;
means for analyzing a reflected signal using time domain reflectometry to determine an apparent dielectric constant K_a of the soil and bulk electrical conductivity EC_b of the soil; and
means for calculating dry density ρ_d of the soil using a predetermined relationship between K_a , EC_b and ρ_d .
26. The apparatus of claim 25, wherein the predetermined relationship between K_a , EC_b and ρ_d is $\rho_d = \frac{d\sqrt{K_a} - b\sqrt{EC_b}}{ad - cb}$, where a , b , c and d are soil specific calibration constants.
27. The apparatus of claim 26, further comprising means for calculating gravimetric water content w of the soil using a predetermined relationship between K_a , EC_b , and w .
28. The apparatus of claim 25, further comprising means for compensating for soil temperature.
29. An apparatus for measuring gravimetric water content of soil, comprising:
a plurality of spikes adapted to be driven into the soil in spaced relationship;
means for applying to said plurality of spikes an electrical signal suitable for time domain reflectometry;
means for analyzing a reflected signal using time domain reflectometry to determine an apparent dielectric constant K_a of the soil and bulk electrical conductivity EC_b of the soil; and
means for calculating gravimetric water content w of the soil using a predetermined relationship between K_a , EC_b , and w .

30. The apparatus of claim 29, wherein the predetermined relationship between K_a ,

EC_b and w is $w = \frac{c\sqrt{K_a} - a\sqrt{EC_b}}{b\sqrt{EC_b} - d\sqrt{K_a}}$, where a , b , c and d are soil specific calibration

constants.

31. The apparatus of claim 29, further comprising means for compensating for soil temperature.